STRUCTURAL DESIGN OF REFRACTORY CONCRETE

BY
R. T. GILES
The Atlas Lumnite Cement Co.
New York, N. Y.

STRUCTURAL DESIGN OF REFRACTORY CONCRETE

BY

R. T. GILES

The Atlas Lumnite Cement Co.

New York, N. Y.

Structural Design of Refractory Concrete

By R. T. GILES
The Atlas Lumnite Cement Co.
New York, N. Y.

REFRACTORY concrete differs from structural concrete in that a calcium aluminate cement and refractory aggregates are used instead of portland cement, sand and gravel or stone commonly used in structural concrete. Refractory concrete is used for continuous exposure to temperature as high as 3000 deg. F. while structural concrete is usually limited to continuous exposure of temperatures no higher than 500 deg. F. to 600 deg. F.

Very little is known about structural design of refractory concrete at this time. Only recently have data been available on the ultimate unit strength of the concrete after it has been exposed to elevated temperatures over long periods of time.* Plots of these data are shown in Figs. 1 and 2. Refractory concrete heated only on one side differs from structural concrete, in that at temperatures above 1500 deg. F. it has a higher strength at the inside face and outside face than it has in the middle of the mass. The strength at the inside face is a result of its exposure to elevated temperatures. The strength at the outside face exposed to the air is similar to that of regular concrete. At some point in the inner part of the concrete there is a weak section or plane similar to a very low quality concrete. To use any one of these strengths individually as a unit design strength would be misleading. It is necessary, therefore, to use the average strength of the concrete for design purposes.

Fig. 3 shows the strengths of the concrete which can be expected if a temperature gradient through

*"Investigation of Certain Properties of Refractory Concrete," Bulletin, American Ceramic Society, Sept. 1939.

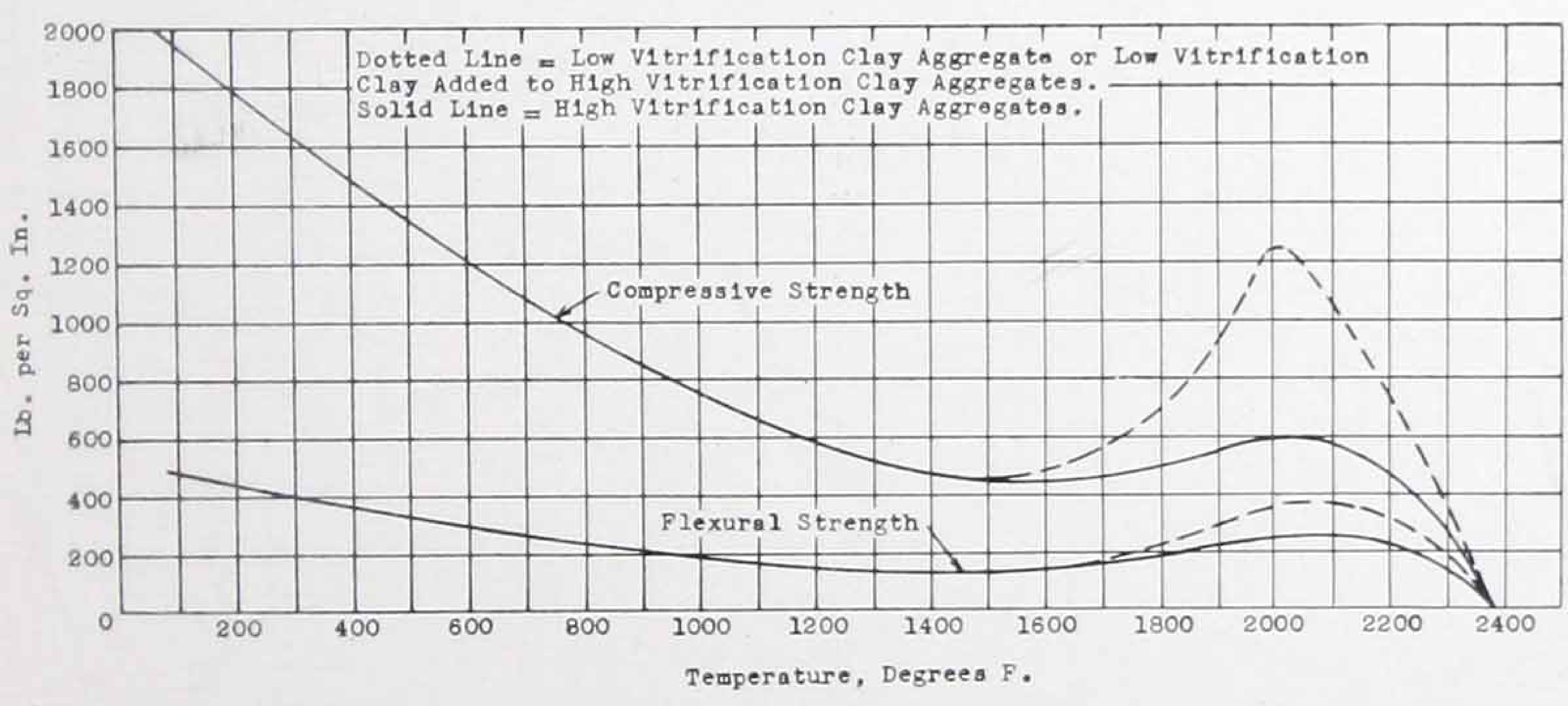

Fig. 1 The average ultimate strength of concrete slabs or walls exposed to elevated temperatures for long periods. These results are applicable to concrete with cold compressive strength of 2000 lb. per sq. in. or more and with cold flexural strength of 500 lb. per sq. in. or more when using calcium aluminate cement as the binder and a strong aggregate in the proportions of 1 bag to 4 cu. ft. of aggregate.

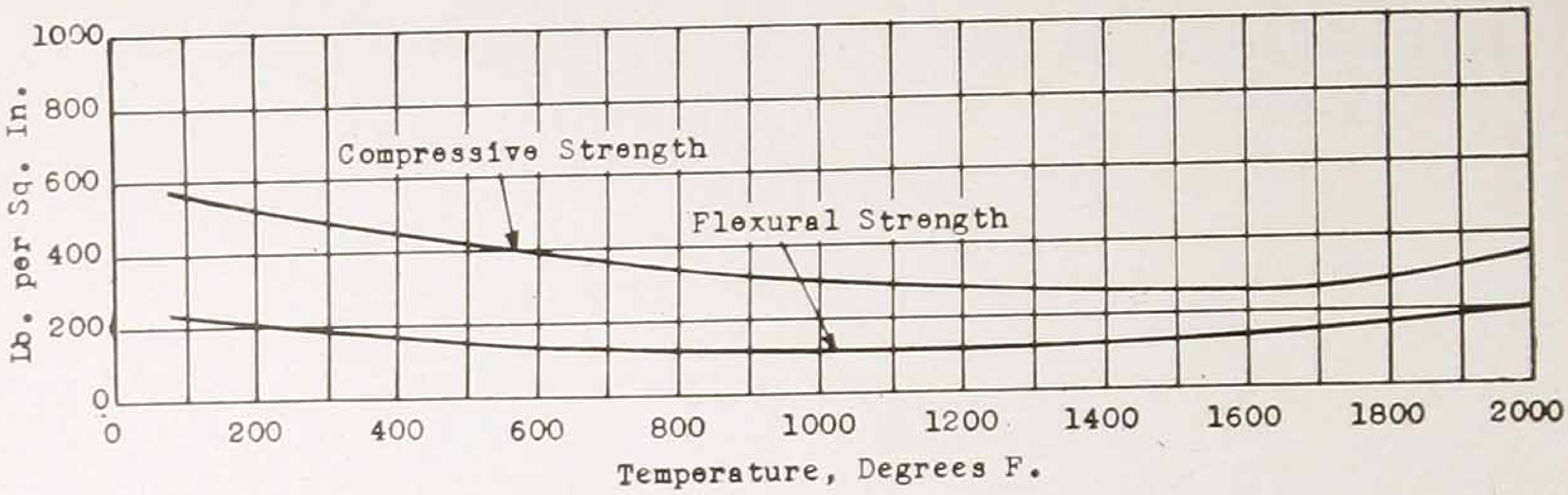

Fig. 2 Ultimate compressive and flexural strength which may be used for determining the average ultimate strength of concrete slabs or walls exposed to elevated temperatures over long periods of time. These results are applicable to concrete with cold compressive strengths of 1000 lb. per sq. in. or less when using a calcium aluminate cement and a weak insulating aggregate in the proportions of one bag of cement to 4 cu. ft. of aggregate.

the wall is plotted and strength of each section used to calculate the average unit strength.

Example: Using a furnace wall of 6″ thick exposed to 2100 deg. F. on the hot face with 300 deg. F. on the cold face. This gives a temperature drop of 1800 deg. F. or 600 deg. F. for each 2″ section. The average temperature in the section containing the hot face is 1800 deg. F. The average temperature of the middle section is 1200 deg. F. and the average temperature of the section containing the cold section is 600 deg. F. By referring to the design chart, Fig. 1, we find the compressive strength using high vitrification aggregate at 1800 deg. F. to be 500 lbs. per sq. in.; the compressive strength at 1200 deg. F. to be 600 lbs. per sq. in.; the compressive strength at 600 deg. F. to be 1200 lbs. per sq. in. By adding 1200+600+500 and dividing by 3, the number of sections, we have 766 lbs. per sq. in. for the average compressive strength for the concrete in the wall.

Example: Using a 12″ wall exposed to 2700 deg. F. on the hot face with a cold face temperature of 300 deg. F. (See Fig. 3) This gives a temperature drop of 2400 deg. F. or 400 deg. F. for each 2″ section. The average temperature in the first 2″ section is 2500 deg. F. which has 0 lbs. per sq. in. compressive strength. The next section has an average temperature of 2100 deg. F. which has a compressive strength of 600 lbs. per sq. in. The next section has an average temperature of 1700 deg. F. which has a compressive strength of 450 lbs. per sq. in.; the next a temperature of 1300 deg. F. and a compressive strength of 500 lbs. per sq. in.; the next a temperature of 900 deg. F. with a compressive strength of 850 lbs. per sq. in., and the outside section an average temperature of 500 deg. F. with a compressive strength of 1350 lbs. per sq. in. By adding 0+600+450+500+850+1350, and dividing by 6, we have 625 as the average compressive strength in lbs. per sq. in. for the 12″ thickness.

Of course, it is realized that the average strength is not an exact measure of the effective strength of a wall whose elements have varying unit strengths. Formulas for exact strength can be integrated by means of the Calculus, but their application is laborious. In addition, consideration should be given to any difference in modulus of elasticity of the concrete at different temperatures. Assuming that these moduli do not differ appreciably, a simple approximation,

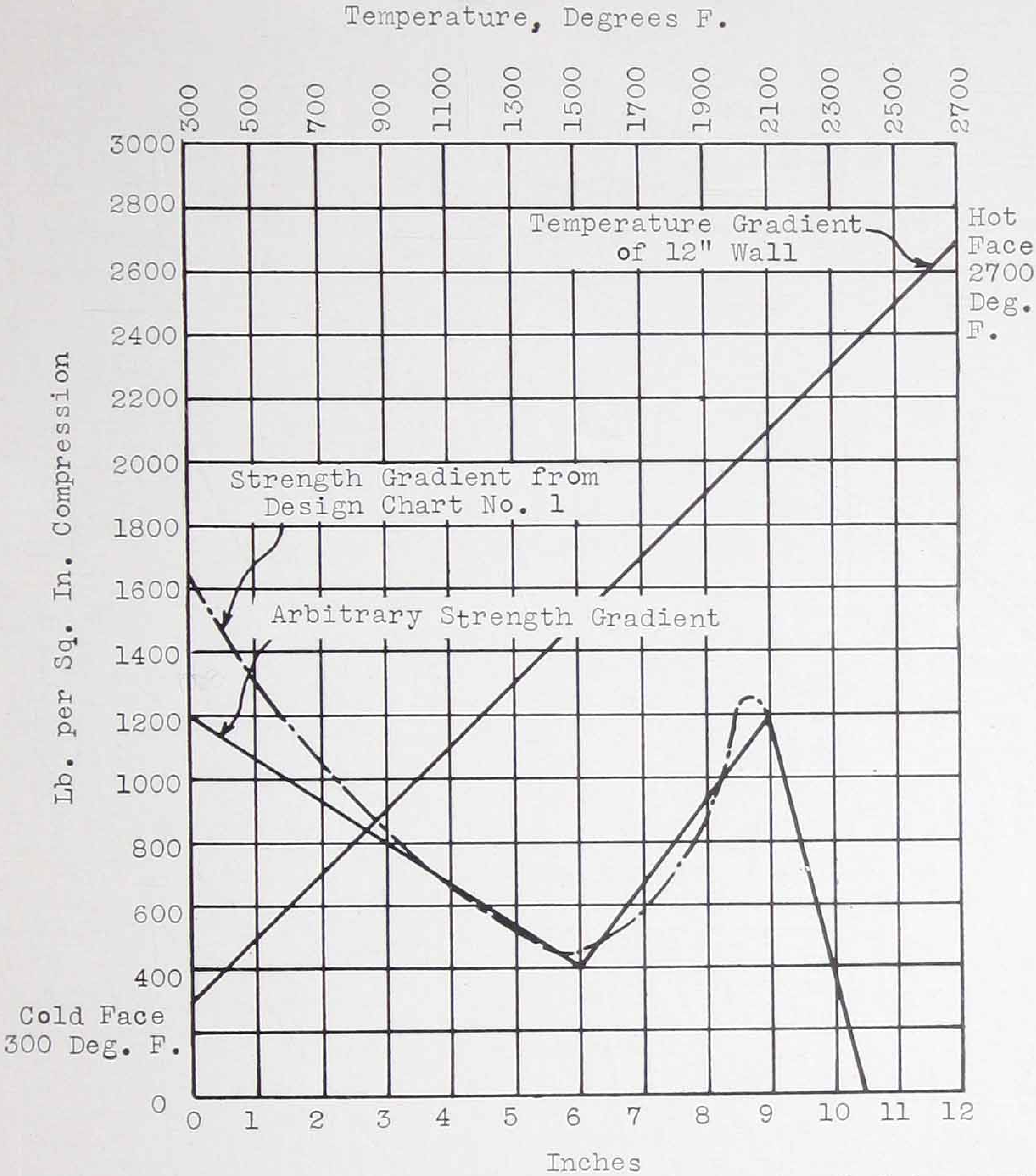

Fig. 3 Wall strength of refractory concrete. Broken line: Strength gradient of refractory concrete wall 12 in. thick exposed to 2700 deg. on hot face; outside surface assumed to be 300 deg. F. Solid line: Arbitrary straight line strength. From this the following formula is taken: Effective Structural Strength in Compression for each linear inch of wall equals 800 times each inch of wall thickness exposed to temperature of 2300 deg. F. and less.

that will cover the most unfavorable conditions ordinarily encountered, is feasible by assuming a wall whose unit strength increases uniformly from zero on the hot side to a maximum on the cool side. Considered as a column, its effective moment of inertia, and therefore its strength, is theoretically two-thirds of that of a wall in which an average strength is assumed to be uniformly distributed.

Hence, if the value found by the method of averages is reduced by one-third, a strength is determined that is believed to be always on the safe side. This will represent the ultimate strength, to which a suitable factor of safety should be applied.

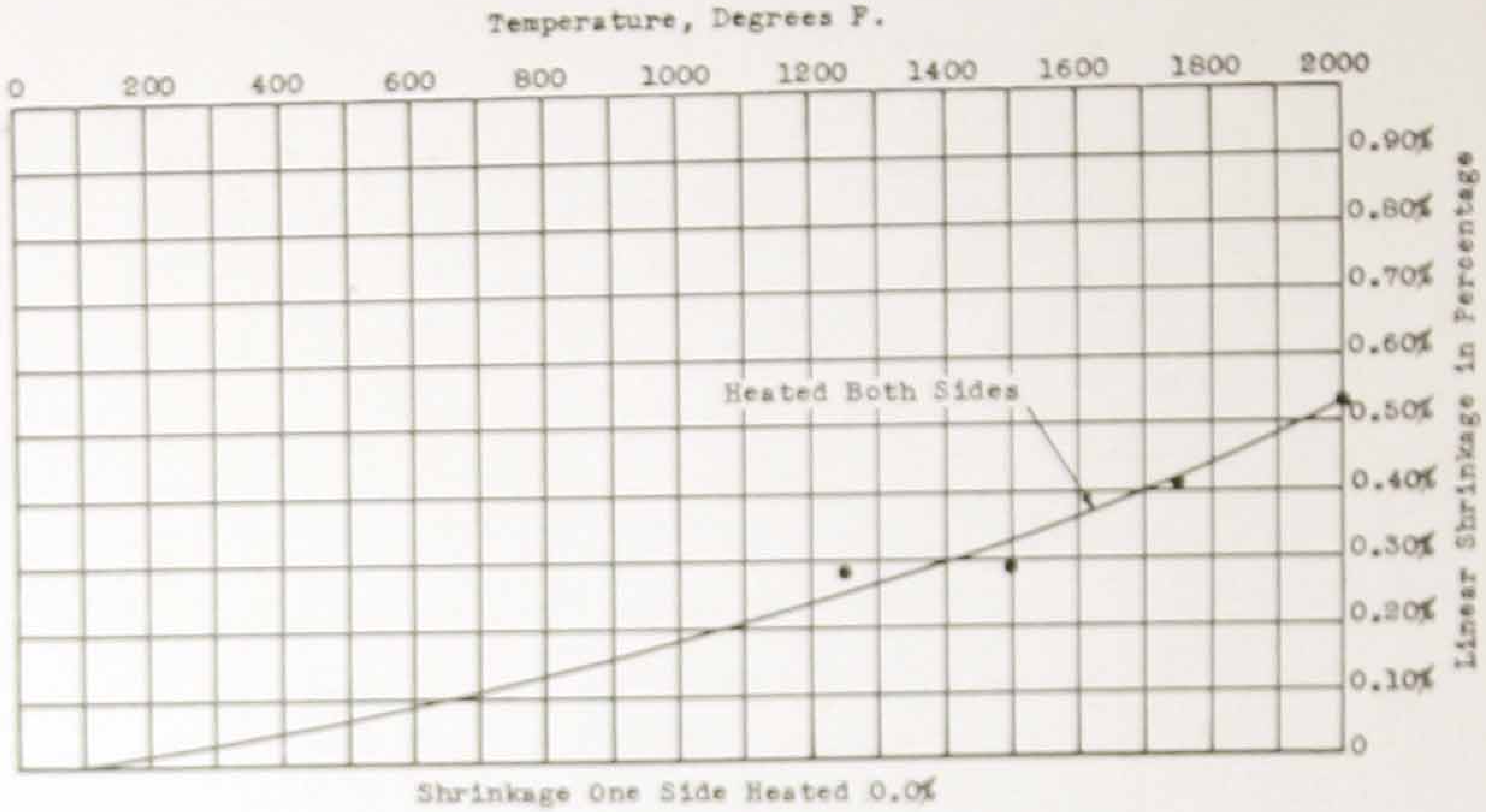

Fig. 4 Chart showing linear shrinkage of refractory concrete.

Volume Changes

In the design of refractory concrete it should be borne in mind that the volume change is much less than when fire brick or prefired units are used. Further, instead of the allowances for expansion, as is customary for prefired units, allowance, if any, should be made for shrinkage in refractory concrete. Characteristic shrinkage is illustrated by the data plotted in Fig. 4. This brings out, of course, the difference in the movement of the walls. When a fire brick wall, well anchored at each end, is heated on one side, the bulge or warping of the wall will be towards the heat. This is due to the expansion of the heated side of the brick. Conversely, when a refractory concrete wall, well anchored at each end, is heated on one side, the bulge or warping of the wall will be away from the heat. This is due to the shrinkage of the hot face of the concrete as opposed to the expansion of the hot face of the prefired brick. As a practical matter, however, the concrete will do little or no bulging, but if sufficient shrinkage is present numerous hair cracks in the hot face will result. Sometimes these hair cracks are too small to be seen by the eye.

The use of reinforcing bars or mesh embedded in refractory concrete has in general been unsatisfactory because it invariably has been so placed that the temperature of the steel exceeded 600 deg. F. In all cases the reinforcing should be so placed that the temperature of the reinforcing steel will not exceed 600 deg. F.

When using regular reinforced concrete design in flat arches the reinforcing bars would be in that part of the concrete having a temperature higher than 600 deg. F. This eliminates this method of construction. However, a method has been devised by which it is believed reinforced flat arches can be made with refractory concrete.

This method is shown in Figs. 5 and 6. The arch is divided into sections. Cast integrally with each

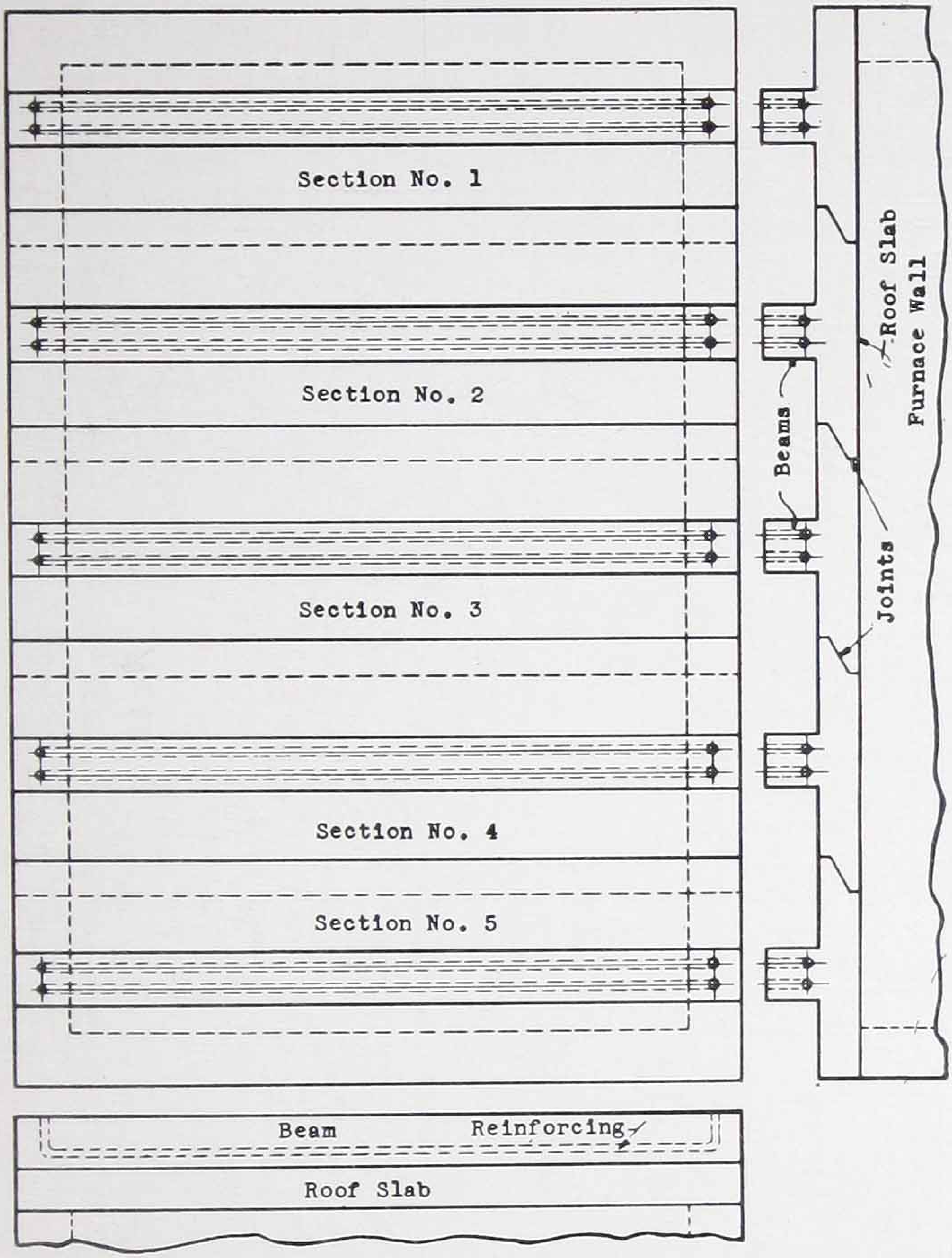

Fig. 5 Refractory concrete flat arch for precast or cast in place sections. Procedure for cast-in-place: Pour sections 1, 3 and 5; remove forms "A" (See Fig. 6); paint joint with fire clay slurry; pour sections 2 and 4.

section of arch itself is a reinforced concrete beam to carry the weight of the arch section. The concrete in the flat portion of the section is composed of the cement and an aggregate of low conductivity. The concrete in the beam surrounding the reinforcing bars is composed of the cement and an aggregate of higher conductivity. The concrete in the flat portion has a low heat conductivity as a result of the use of the insulating aggregate, while the concrete in the beam has a higher heat conductivity as a result of the use of dense aggregates. The higher conductivity concrete in the beam and the lower conductivity concrete in the slab each has an important bearing on the temperature of the reinforcing steel. Stated otherwise,

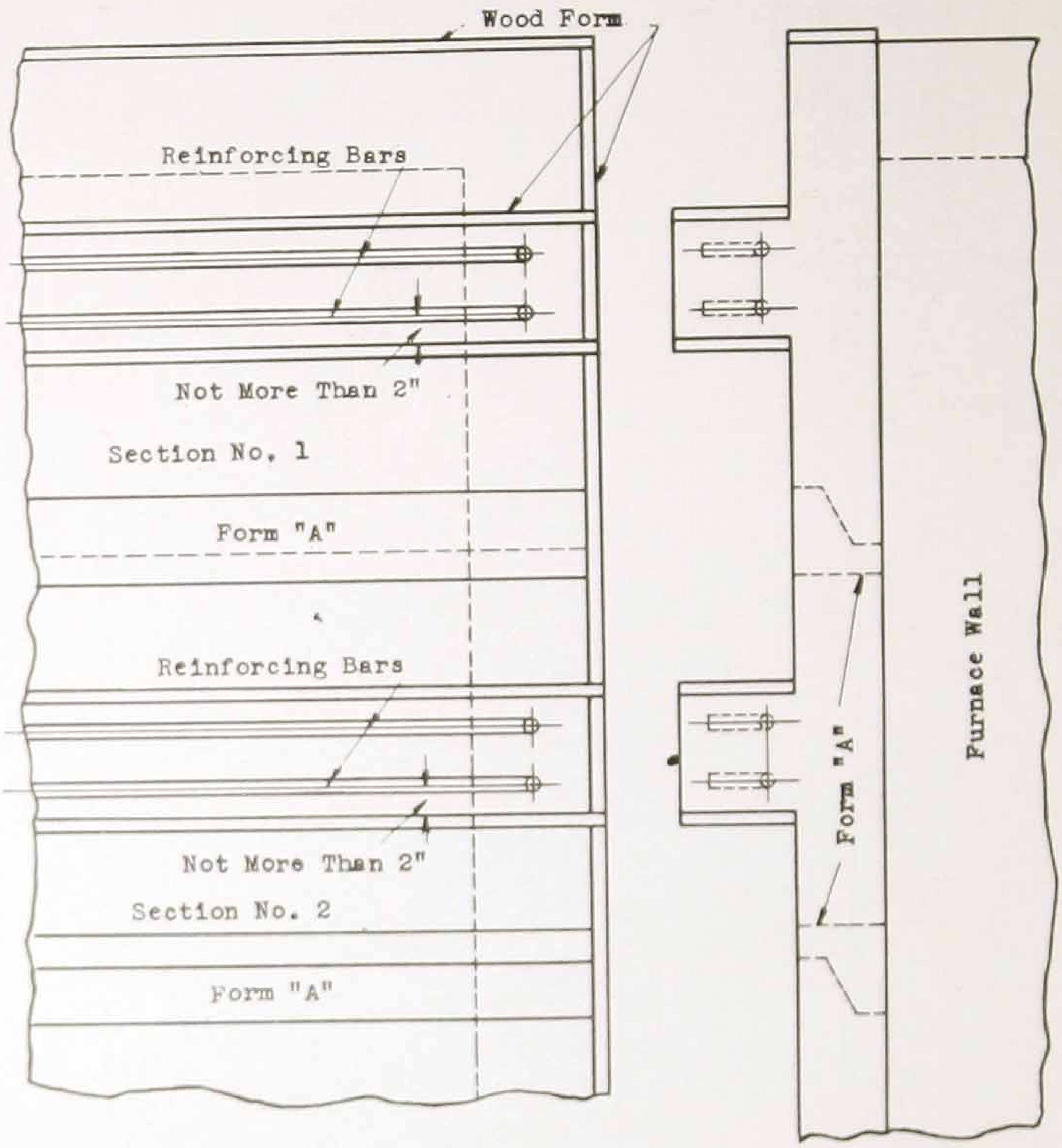

Fig. 6 Diagrammatic view of forms and reinforcing bars in place. This method used in constructing flat arch shown in Fig. 5.

the difference in the conductivity of the two concretes has an important bearing on the required thickness of the slab to maintain a temperature in the reinforcing steel no higher than 600 deg. F.

While this method has been shown as applied to flat roof slabs, it can be applied to vertical side walls or floors as well. The method is not limited to temperatures for which satisfactory insulating aggregates can be obtained. Surface coats, layers of concrete or units of highly refractory materials can be used to protect the insulating concrete. The protected arch or wall is then serviceable at much higher temperatures than is the unprotected insulating concrete. Figs. 7, 8, and 9 show the thickness of the slab using insulating aggregates for concrete with a K factor of 2, 3 and 4 when used with a concrete in the beam with higher K factors. In calculating the thickness of roof slab use Figs. 7, 8 and 9 for reinforced beam construction where the reinforcing is not more than 2" from the exposed side of the beam as shown in Figs. 5 and 6.

While the charts show K factors much higher than 10, it has not

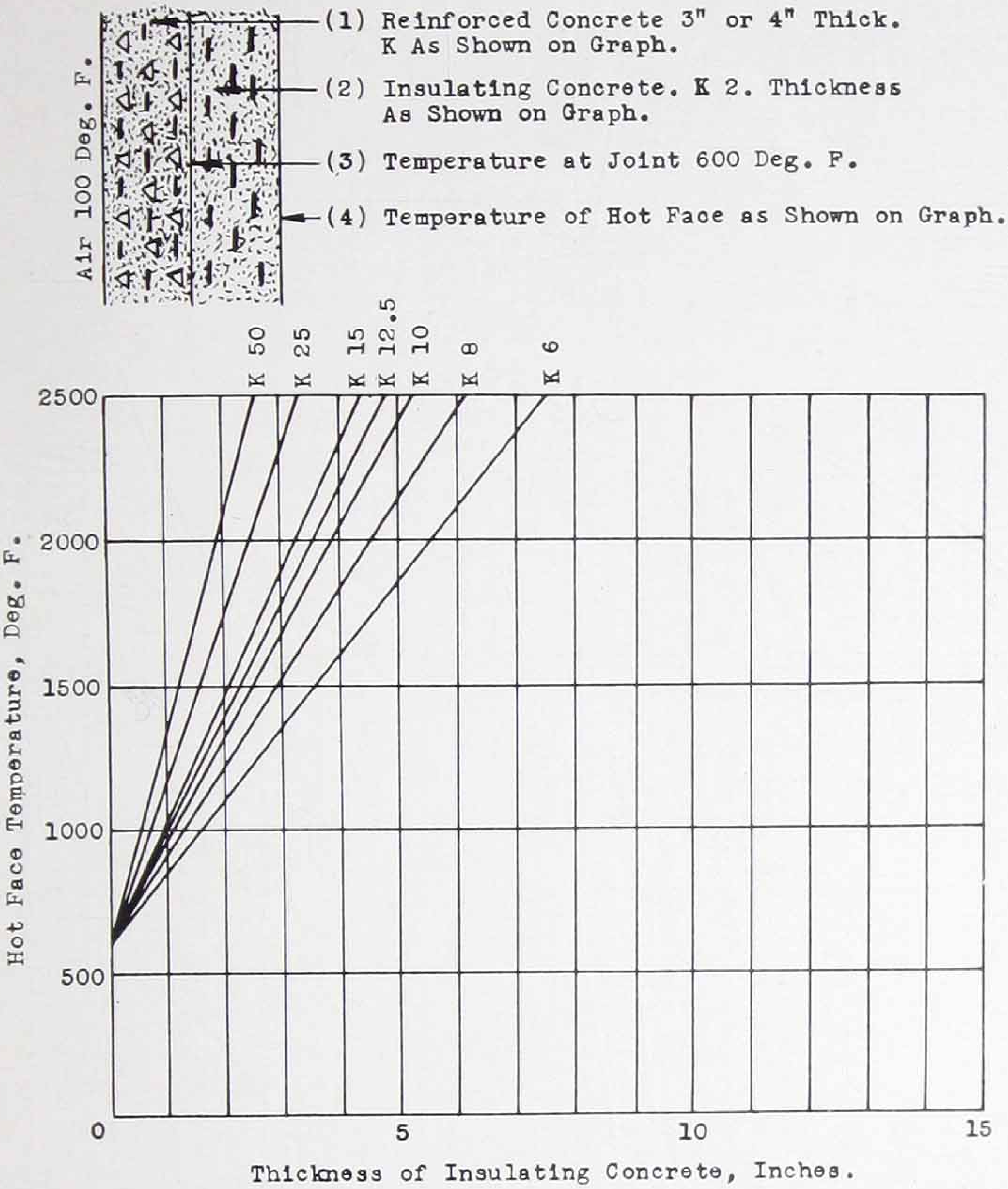

Fig. 7 Thickness of slab using insulating aggregates for concrete with a K factor of 2, when used with a concrete in the beam with higher K factors.

so far been demonstrated than an economical concrete can be developed which will have a much higher K factor. Indications are that at temperatures of 600 deg. F. and lower, the use of olivine or magnesite offers the greatest promise but that the most that can be hoped for from either of these aggregates used in concrete is to develop a K factor of approximately 15. For concrete made of trap rock a K factor of 8 may be assumed, while with aggregate made from old fire brick a K factor of only 6 can safely be used.

It has not been definitely proven that a temperature somewhat higher than 600 deg. F. could not be used for ordinary carbon steel. However, it is felt that this temperature is conservative and until such time as experience shows it to be too conservative it should be used.

Application to High Temperature Furnaces

Refractory concrete will undoubtedly be used in furnaces, the temperatures of which are entirely

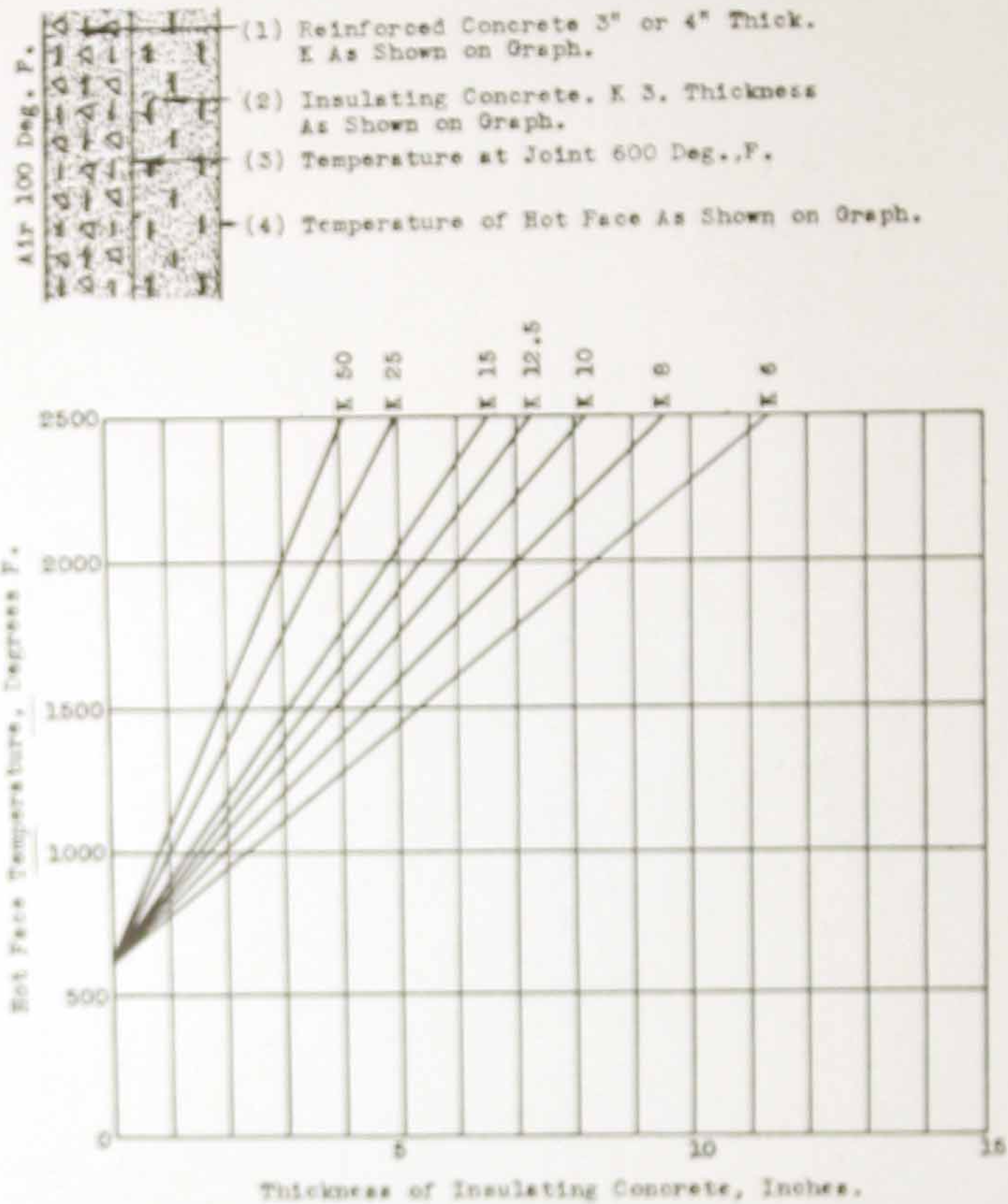

Fig. 8 Thickness of slab using insulating aggregates for concrete with a K factor of 3 when used with a concrete in the beam with higher K factor.

too high for any insulating grog so far offered for sale commercially. It is therefore necessary to develop other methods of applying refractory concrete to the higher temperature furnaces. Again we find the roof the main problem and again will it receive the greatest consideration. While it is true furnaces in the past have primarily used sprung arches for the roof, it is possible the realization of the value of refractory concrete may completely change this. Flat arches in many furnaces have a very decided advantage and, since this is so, flat arches have received the greatest attention.

By referring to Fig. 10, the details of a flat arch, either precast or cast in place, are seen. It will be noted that the principle of quick dissipation of heat to lower the temperature in the steel supports is used in this design. This is accomplished by extending the steel supports above the top of the concrete sections. "I" beams can

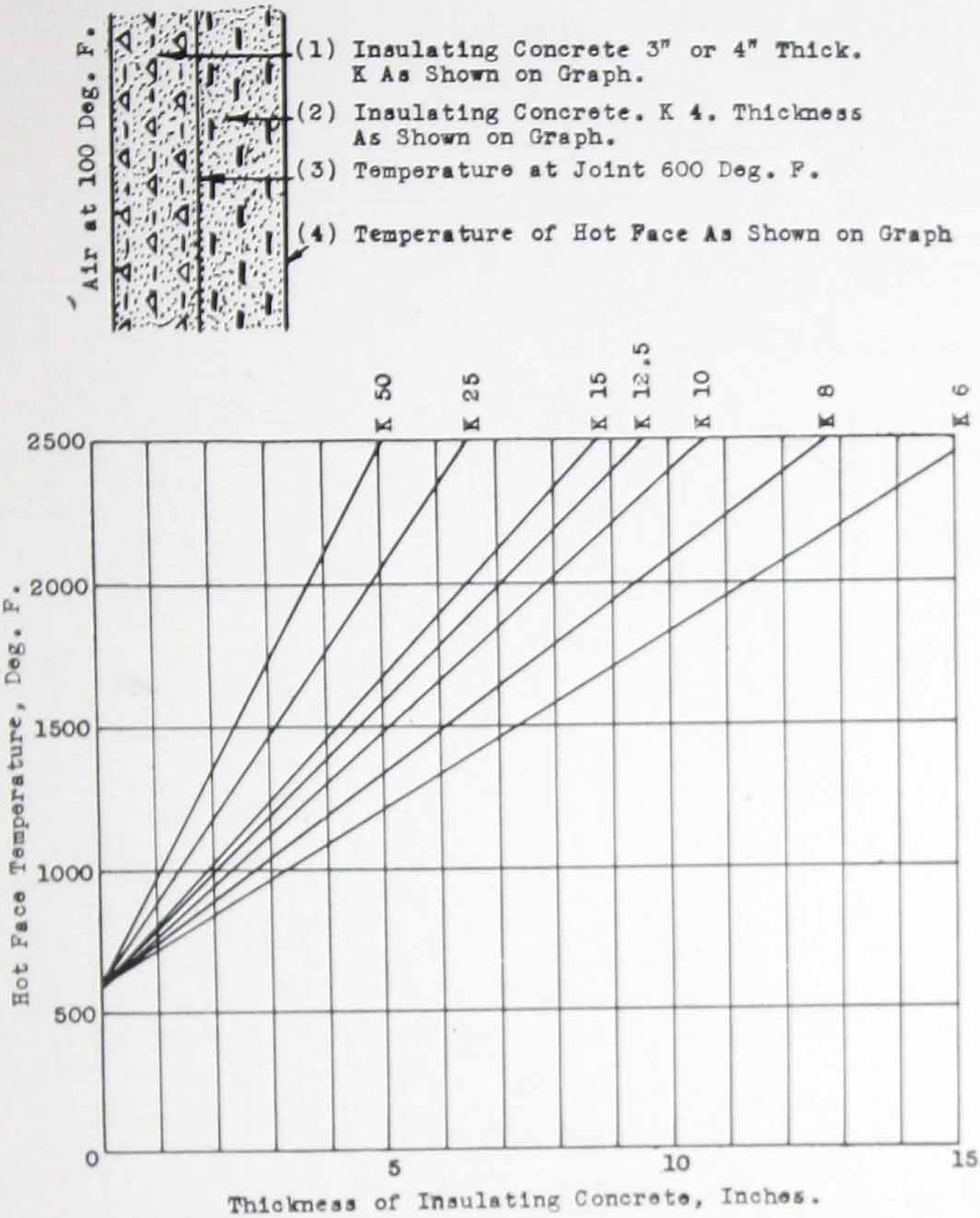

Fig. 9 Thickness of a slab using insulating aggregates for concrete with a K factor of 4 when used with a concrete in the beam with higher K factor.

of course be used in place of the welded bar supports.

In this method conditions are rather ideal; whereas, when reinforcing steel is embedded in the concrete, the expansion of the steel and the shrinkage of the concrete when exposed to elevated temperatures, theoretically at least, tend to break down the concrete. The method shown in Fig. 10 is much more compatible with the volume change of the two materials when heated to elevated temperatures. It is noted that the shrinkage of the concrete, to some extent at least, compensates for the expansion of the steel.

While no installations using the method shown in Fig. 10 have been made at the present time of writing, Fig. 11 shows a full floating flat arch 4 in. thick and 8 ft. square, which is the principle util-

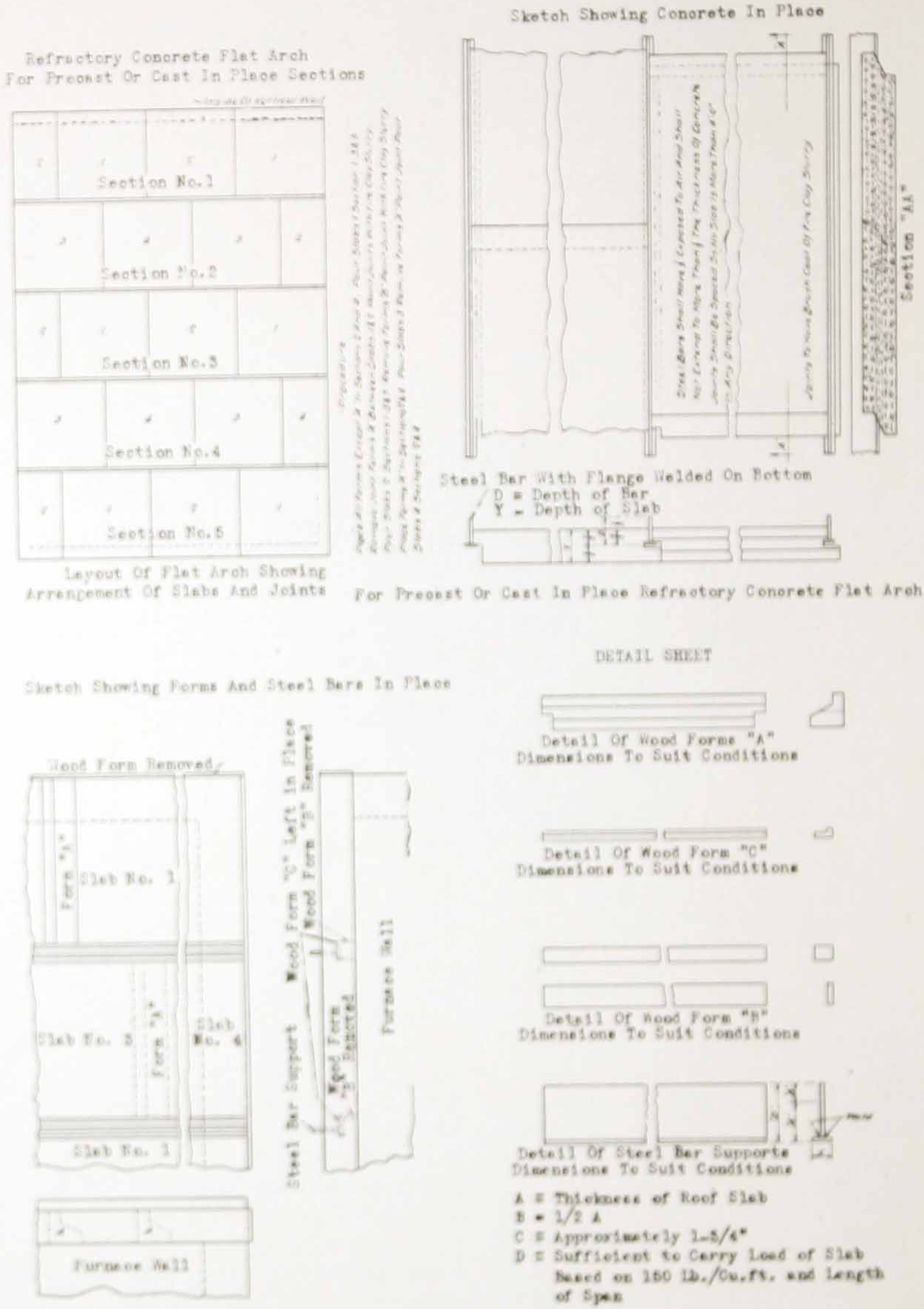

Fig. 10 Diagrammatic plan of refractory concrete flat arch for precast or cast in place sections.

ized for this method of construction.

Fig. 12 also illustrates a method of construction for precast or cast-in-place sections. This method offers a simple and flexible method which can be used for large sections.

Figs. 15 and 16 illustrate the method of reinforcing shown diagrammatically in Fig. 12, except that there were no cross angles installed.

While the information given relative to the amount of steel buried in the concrete and the amount exposed to the air is thought conservative, it should be borne in mind that more experience will be needed to lay down any hard and fast rules.

The question of sprung arches is relatively simple. They may be cast in place or precast in sections and lifted into place with a crane. Sections of arches with a 14′0″ span, weighing 3 tons with no reinforcing, have been precast and set in place with a crane. Where doubt exists about the strength of the concrete in an arch section it can be reinforced with angle irons on the outside corners. When so used one flange of the angle is exposed to the air for rapid dissipation of the heat to maintain a low temperature in the steel. The angles must be bent to conform to the radius of the arch and fastened together at the ends and several points in the middle.

With reference to Figs. 13 and 16, this method may also be applied to flat arches and wall sections.

It is doubtful if in many cases it will be desirable to reinforce the

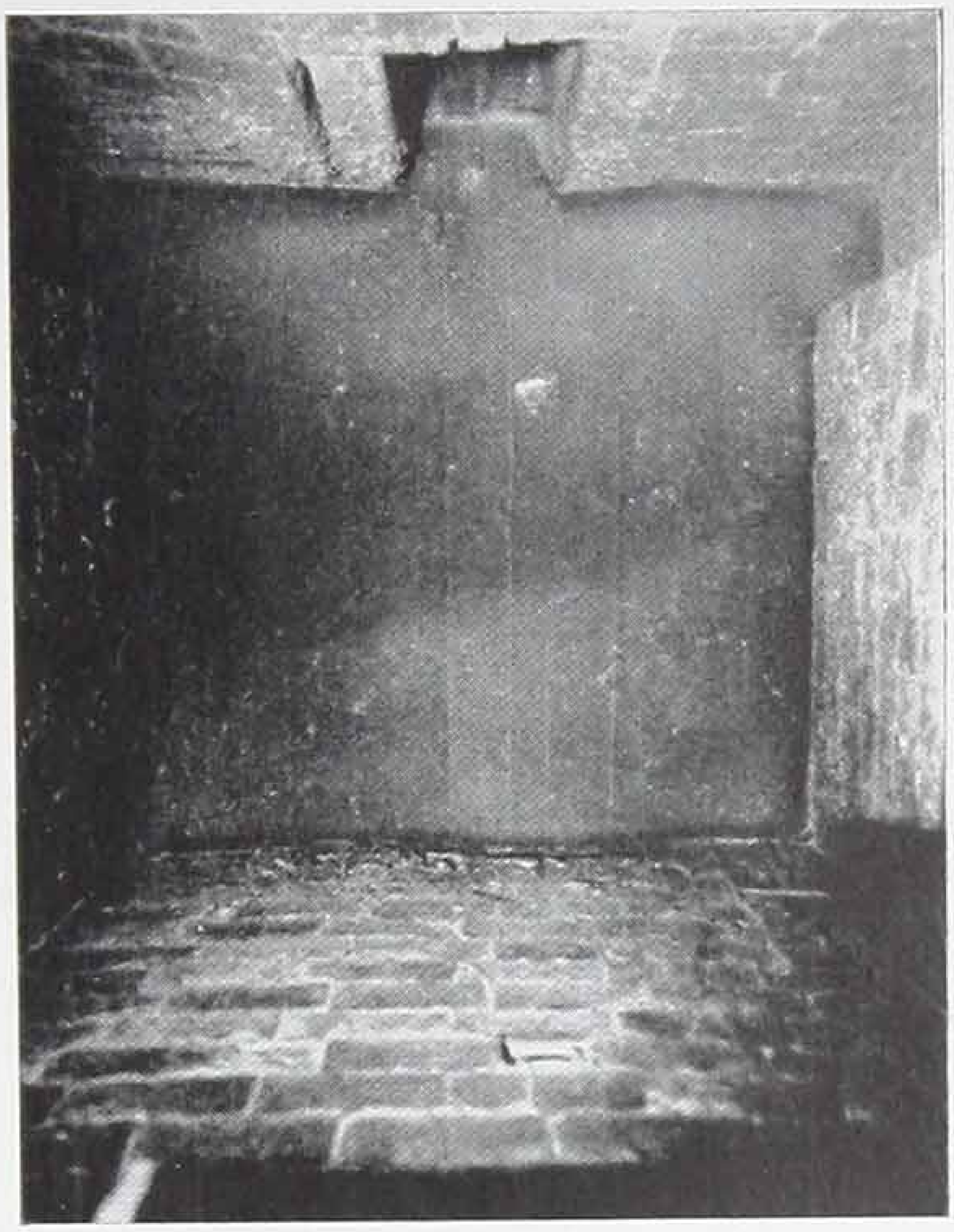

Fig. 11 No installations have been made using the reinforcing method similar to that shown in Fig. 10. The above illustration shows a full floating flat arch 4 in. thick and 8 ft. square, which is the principle utilized for this method of construction.

vertical or side walls of a furnace. However, in Fig. 14 reinforced side walls are shown. (See also Fig. 17). One side shows bars embedded in the concrete, while the other shows angle irons with one flange embedded in the concrete and the other flange exposed to the air to facilitate the dissipation of heat and maintain a low temperature in the angle. It is obvious that the methods of construction can be interchanged to a considerable extent. For example, the methods shown for reinforcing the side walls can be used for the bottom. It is important to remember that the temperature of the steel should not exceed 600 deg. F. in any case. The bottom in this sketch shows a method of construction similar to that shown in the roof arch, Figs. 5 and 6. The roof shows a method of construction similar to that shown in Fig. 10.

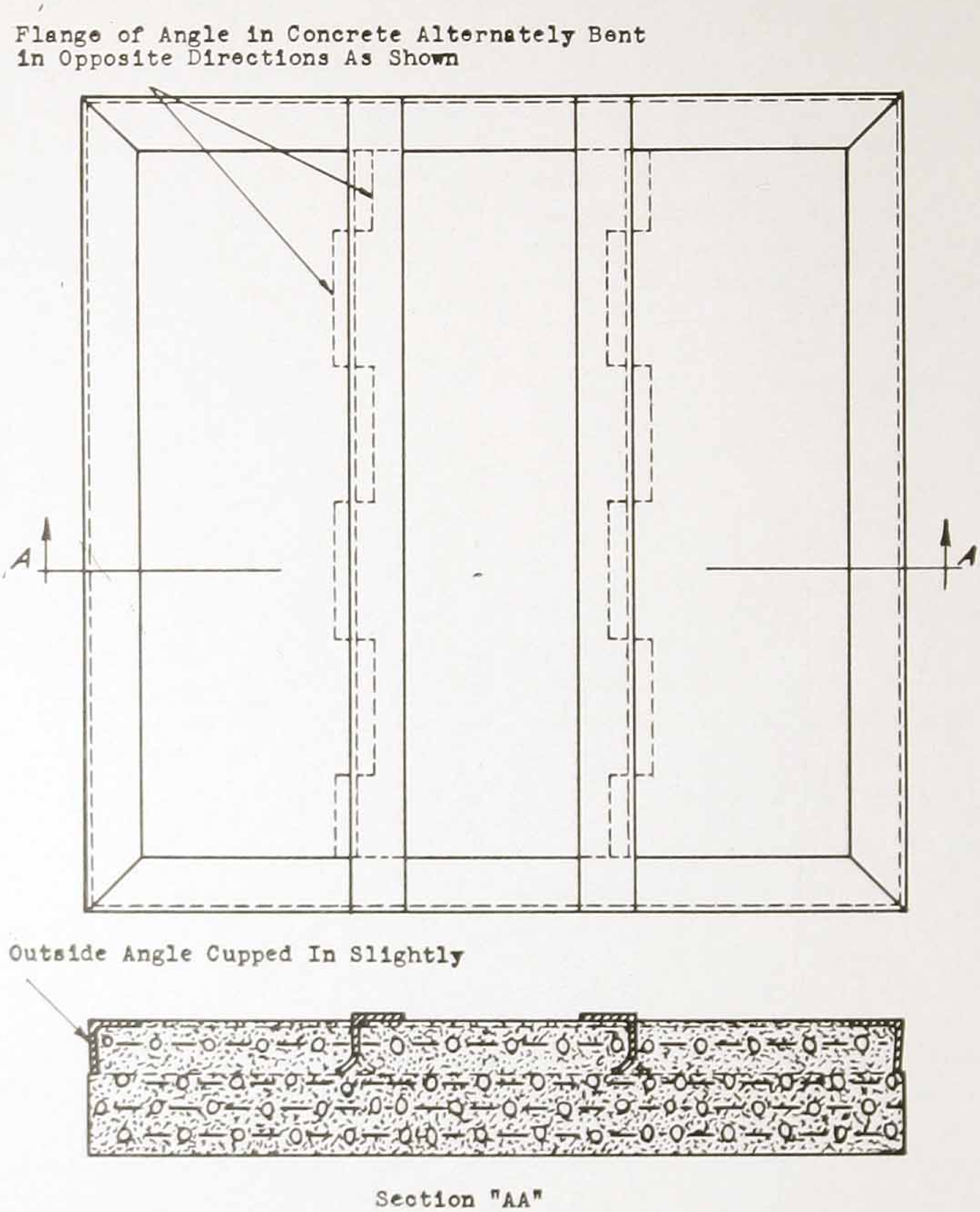

Fig. 12 Section with angle iron reinforcing suitable for arches, walls and bottoms.

While the side walls show the reinforcing in one direction it can be used in the opposite or both directions if desired or supplemented with wire mesh as shown.

When refractory concrete is dependent wholly upon its own strength it would appear logical to limit the dimension of any slab to not more than 4′-0″ in any one direction. However, when the refractory concrete slab is reinforced by other methods it is felt the size of the slab can be increased to any size which the particular method will permit.

Fig. 10 illustrates a method in which the maximum dimension should be limited. Figs. 5 and 6 illustrate a method in which the maximum dimensions of the slab would be largely dependent upon the strength of the reinforced beam. The side walls in Fig. 14 illustrate a method in which it is felt the dimensions of the concrete

might be very large—in fact, with almost no limit. This is also true of the method shown in Fig. 12.

Repairs

While the method of construction is important there are under certain conditions other considerations of equal importance. Under severe conditions where repairs are frequent and inevitable, the means for making replacements is of equal if not greater importance. No great difficulty is encountered in repairing the bottom of most furnaces. After the slag is chipped off, another layer of refractory concrete can be placed on top of that portion of the concrete slab remaining.

Much the same condition exists with relation to the side walls except that forms are necessary to form the inside surface while the remaining concrete acts as the outside form. In large furnaces the side walls may be repaired by shooting a refractory concrete mortar with a cement gun.

Roof arches offer a greater problem and it is felt the method shown in Fig. 10 offers the simplest method of repair especially if precast units are used in the original construction. For example, if slab No. 2 in Section No. 3 needed replacement it would only be necessary to remove slabs No. 1 and 2, insert a new slab for No. 2 and replace slab No. 1. This repair could in many cases be made without serious interference with operation and without materially

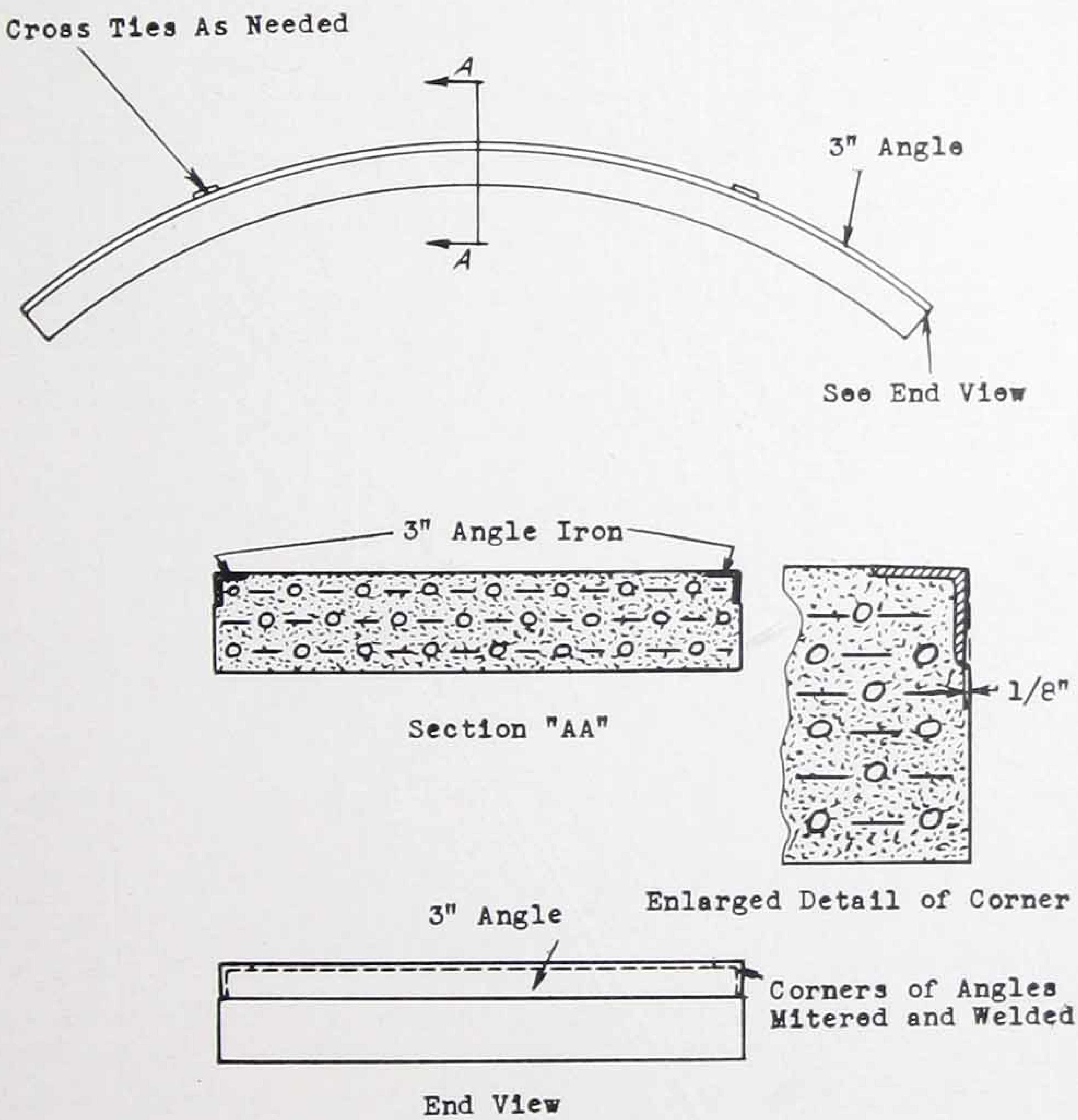

Fig. 13 Sprung arch section showing angle iron frame.

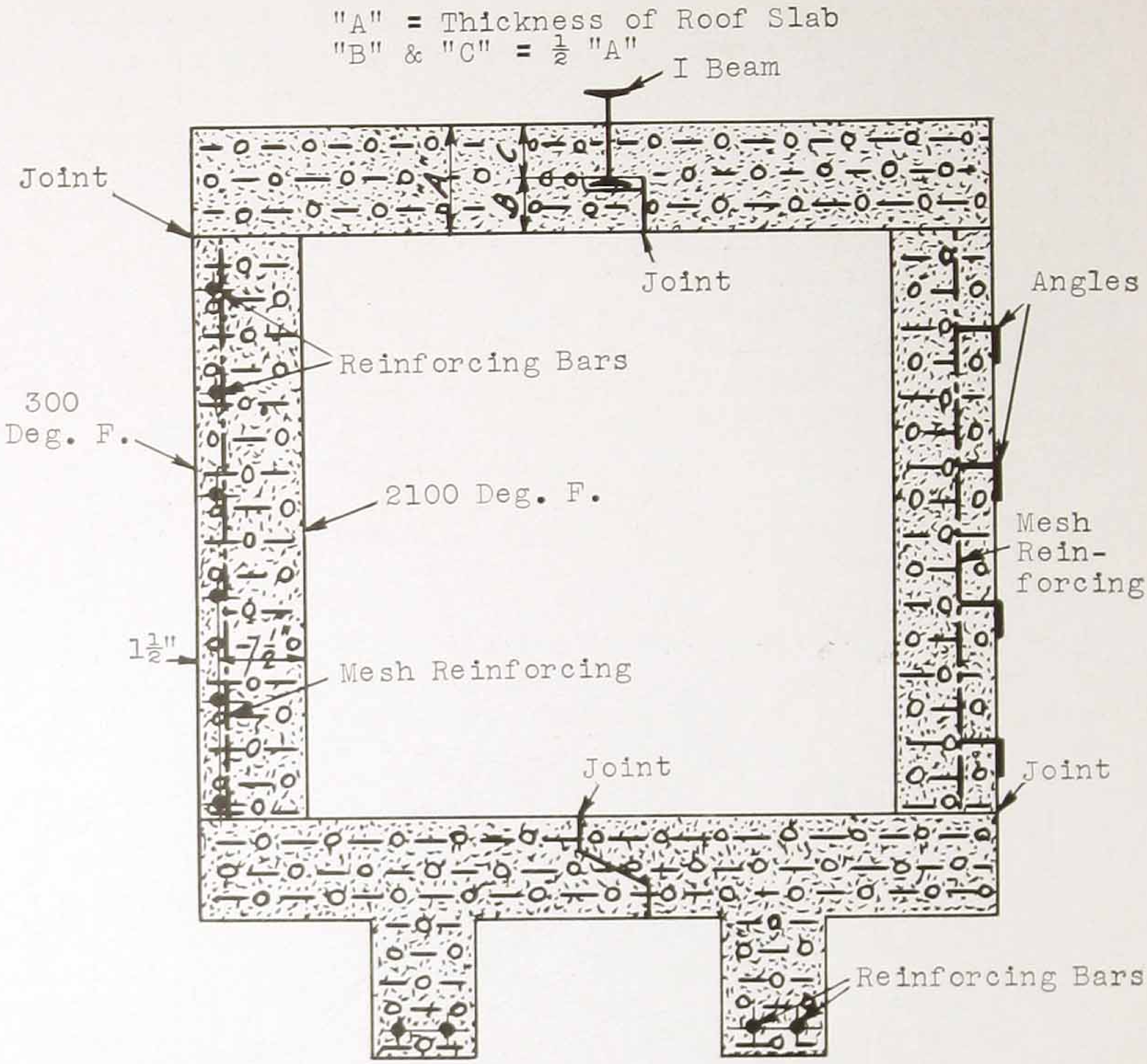

Fig. 14 Illustrating several different methods of reinforcing refractory concrete. A different method of reinforcing is shown in each side. Where metal reinforcing is embedded in the concrete, it should be so placed that the temperature of the steel will not exceed 600 deg. F. All joints should be given a paint coat of fire clay slurry.

dropping the temperature in the furnace. The application of the fire clay slurry to these joints during construction has an important part in the removal of these sections. If a highly refractory clay is used, a plane of weakness at each joint will exist which will greatly facilitate the removal of the slabs.

A cement gun can also be used for repairing these slabs but it would prevent the removal of any of these slabs for replacement at a later date. The repair of a roof slab as shown in Figs. 5 and 6 would require the use of a cement gun or the removal of a complete section. Under these conditions it is felt this method of construction is best adapted to furnaces which seldom require repairs or replacement.

Where conditions are such that it is desirable to use reinforcing which will attain a temperature higher than the 600 deg. F. maximum for carbon steel, special steels should be used.

Size Limitations

It is commonly accepted that brick walls of 4½" thickness are

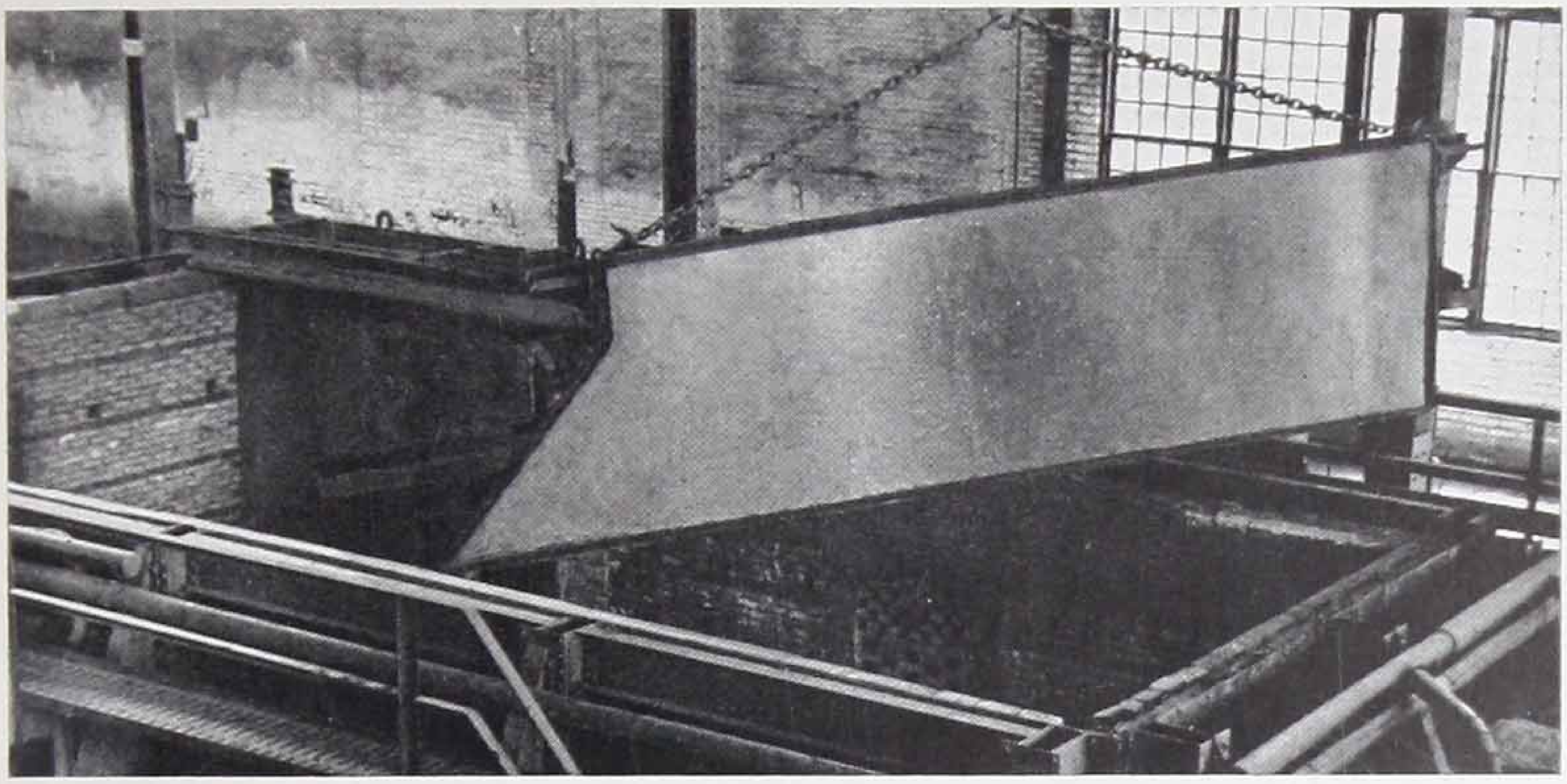

Fig. 15 Example of the method of reinforcing shown in Fig. 12 except there were no cross angles.

not suitable for heights greater than about 3 feet, while 9″ brick walls should be limited to a height of 8 feet; 13½″ brick walls to a height of 12 feet, and for greater heights the brick walls should be 18″ or more thick.

Refractory concrete can be reinforced so that practically any thickness can be used in walls of almost any height. Assuming that the concrete wall is 80% as thick as the brick wall, approximately the same heat loss will result, while there will be much less heat storage in the concrete. This is explained by the fact that if clay fire brick are crushed to granular sizes, mixed with the cement and cast as concrete, about 15% greater porosity exists in the concrete than in the brick before being crushed. This increase in porosity results in greater insulating value and decreases the weight per cubic foot which, when combined with the reduction in thickness for the concrete wall, makes its weight only about 67% that of brick wall of the same furnace.

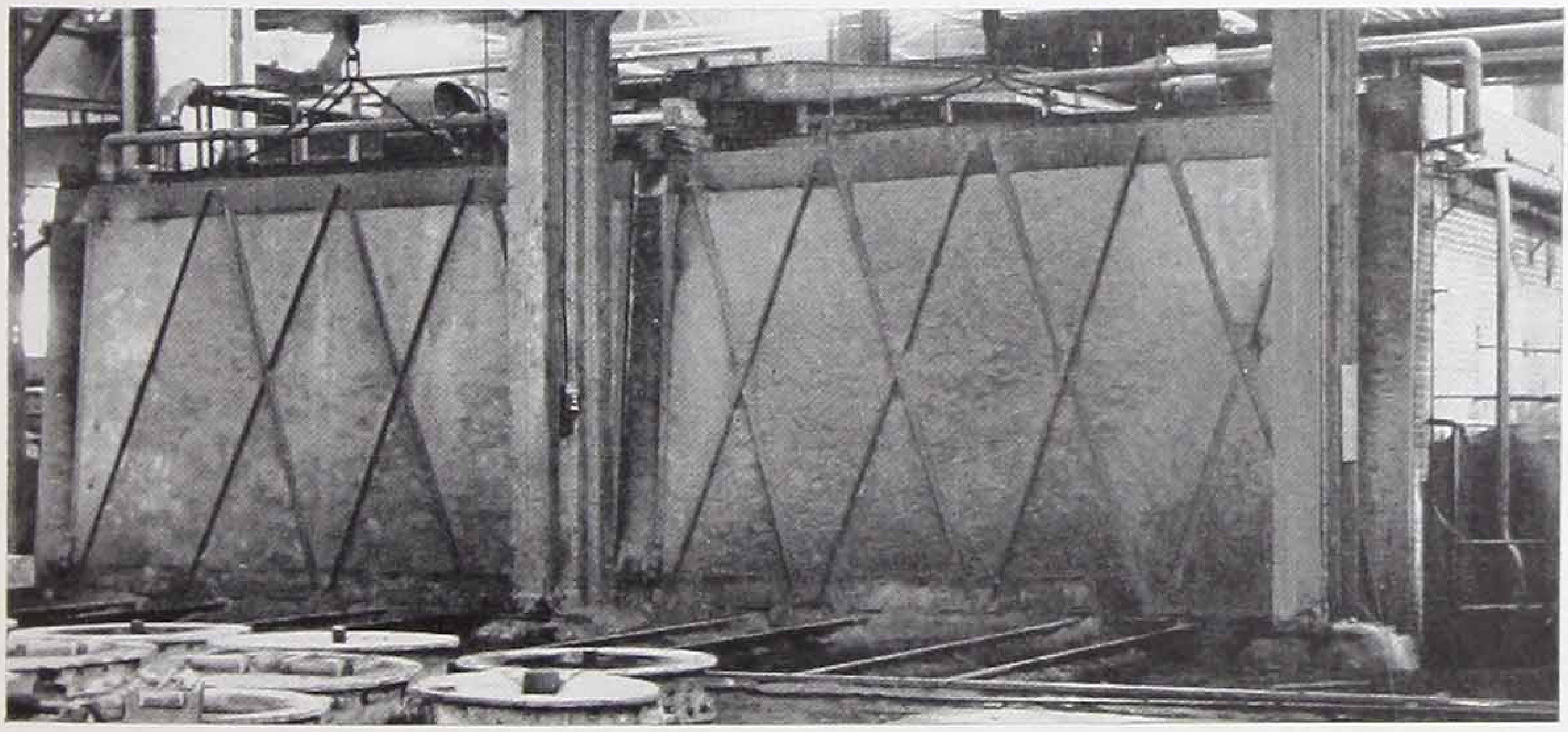

Fig. 16 Another example of the method of reinforcing shown in Fig. 12 except there were no cross angles.

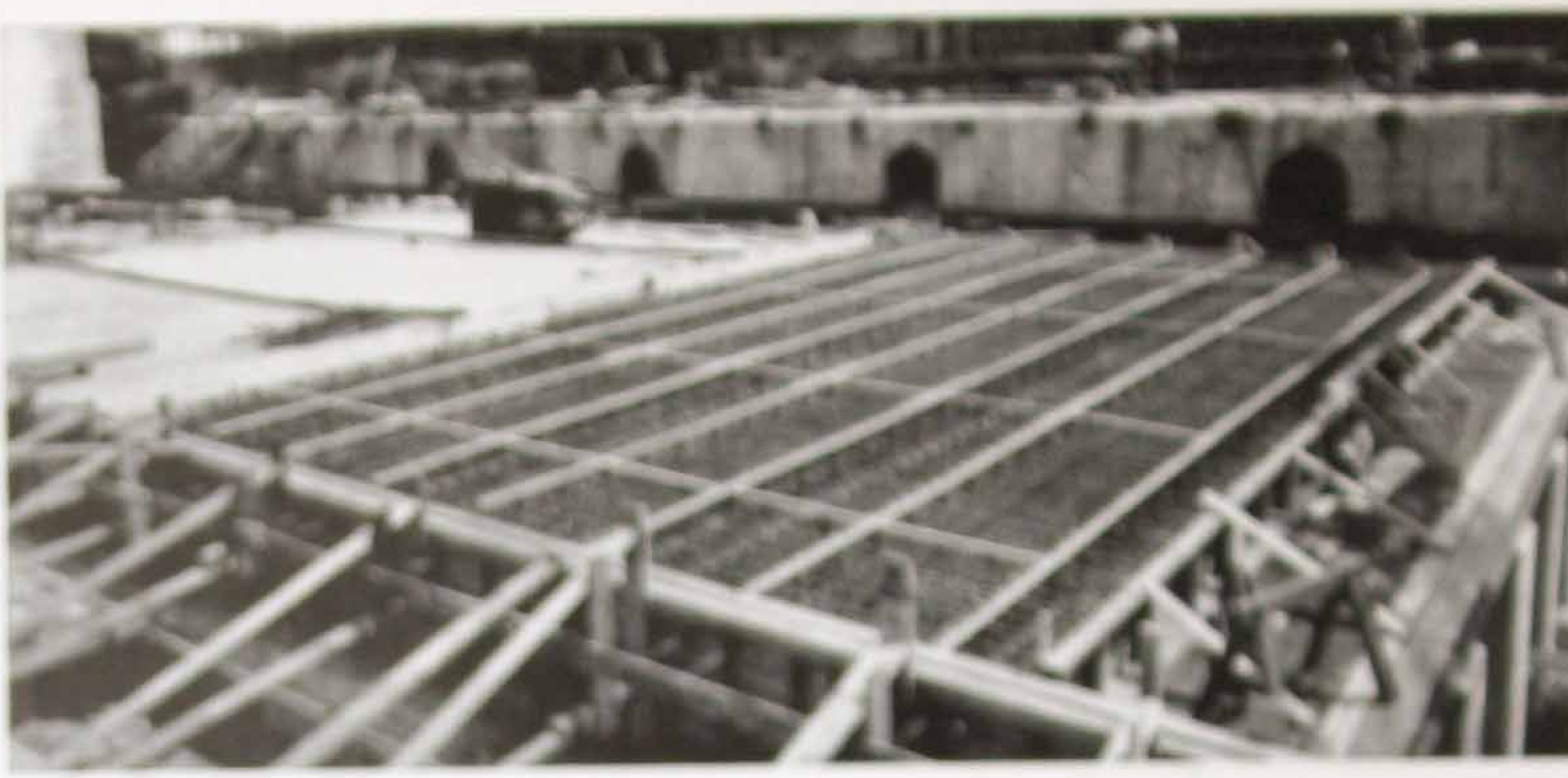

Fig. 15 Example of the method of reinforcing somewhat similar to that shown in the left vertical wall of furnace shown in Fig. 14.

On the above basis, a furnace requiring 85,000 fire brick (5000 cu. ft.) would require only 4000 cu. ft. of concrete. Assuming that the material costs ($40/M) for brick and concrete are the same price per cubic foot, the savings on materials alone are 20% or $700.

In addition, the labor cost would undoubtedly be reduced. The total weight would be only 67% or a reduction of 100 tons which would require lighter foundations—a considerable item under certain conditions.

When it is realized that this reduction in wall-thickness and weight in no way affects, and in some instances may improve, the efficiency, careful consideration should be given to refractory concrete in designing furnaces.

In many of the low-temperature furnaces now being built insulating concrete can be employed at reasonable cost due largely to the fact that the insulating grog is much lower in cost per pound in aggregate form than when made up into brick. The cost of regular fire brick grog is, speaking generally, higher per pound than the same material made up into brick. This is probably explained by the fact that several firms are making a lightweight clay grog especially for insulating concrete, whereas no firm is making a heavy clay grog for use in refractory concrete.

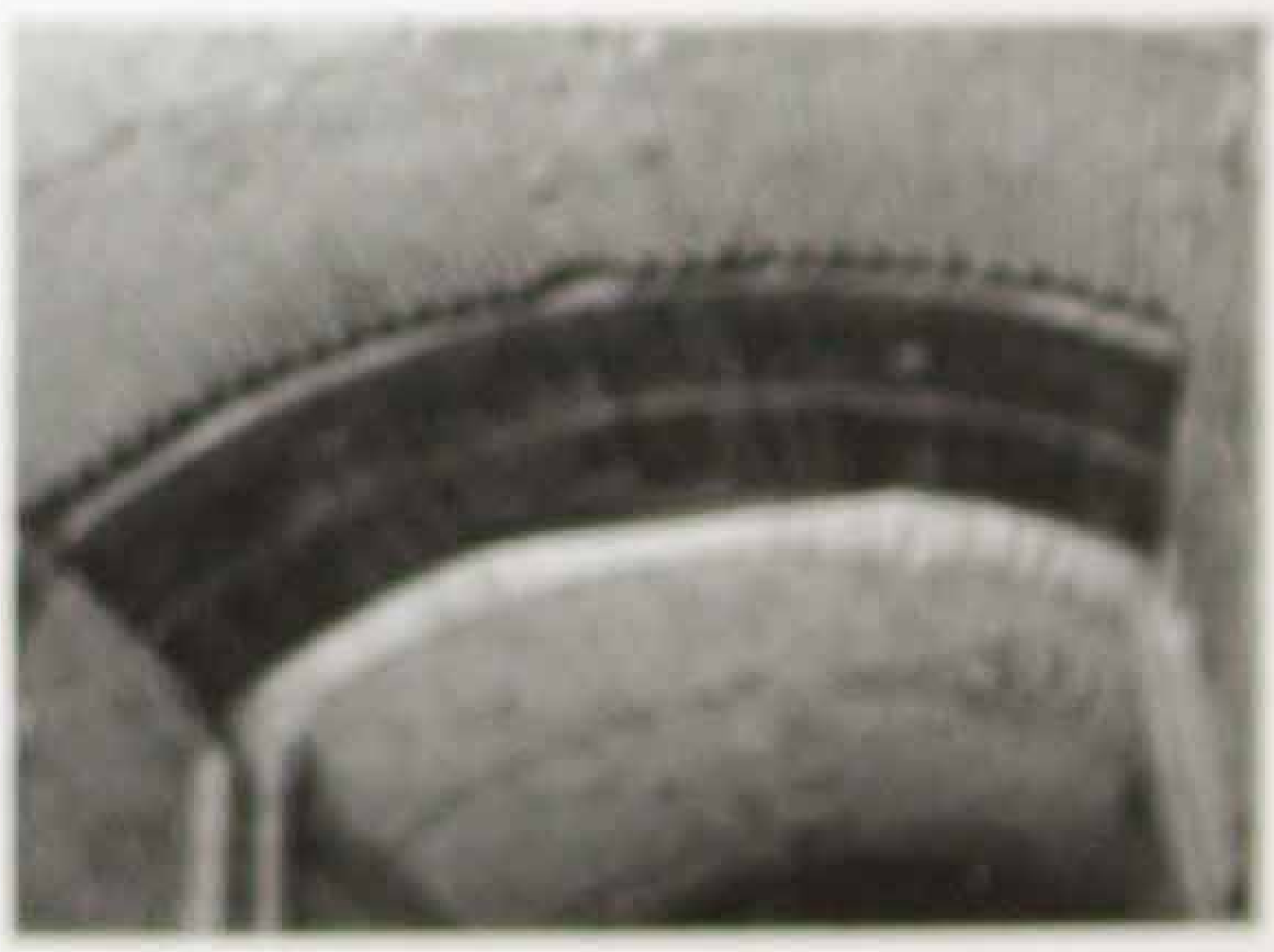

Fig. 17 Unreinforced precast refractory concrete arch sections, 16 ft. span. Each section weighs 2 tons. The method of reinforcing shown in Fig. 15 would have been required had it been necessary to remove these sections on occasions.

Reprinted from
"Industrial Heating"
1940